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Energy price spread as a driving force for combined generation investments: A view on Europe

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ABSTRACT

Combined generation of heat, cooling and power has a large potential to increase its share in distributed generation of energy. Such investments are driven by energy savings which result to operational profits. These profits are very sensitive to the prices of the competitive energy products: electricity and gas. In this work a theoretical indicator is developed between energy prices, the technical characteristics of cogeneration and conventional generation equipment and the investment viability. Through this indicator, the operational profitability of cogeneration equipment is mapped and discussed. Empirical rules are extracted which can give a clear view of the sensitivity of energy prices on energy efficiency investments. The European cogeneration status quo is analyzed in terms of energy prices and market share. The developed indicator is also used, to analyze market related barriers and highlight the importance of energy pricing policy as a tool to minimize the risk exposure of energy efficiency investments.

1. Introduction

Combined generation of electricity, heat (CHP) and in many cases cooling utilizes the primary energy of a fuel even more efficiently, economically, reliably and with less harm to the environment than separate production means [1]. It is recognized by the EU as one of the most efficient ways to produce end-use energy from fossil fuels [2]. CHP systems are touching all five dimensions (energy efficiency, secure supplies, energy market, emission reduction, research and innovation) of the newly announced EU's Energy Union.

Two big categories of such systems can be identified: a) centralized power plants which extend their primary activity of electricity production to heat production and distribute it via other network to the end consumers (main producers), and b) distributed generation plants which benefit from the increased efficiency generating electricity and heat wholly or partly for their own use as an activity which supports their primary activity (autoproducers). Fig. 1 shows the share of electricity generation from CHP technologies for 2012 sorted by the CHP autoproduction share. This work focuses on the latter category as the energy prices and their spread which is examined in this work is one of the strongest drivers of such investments.

Autoproducers mainly exist in the industrial and the tertiary sector (medium scale CHP) and to a smaller extent to the residential sector (micro-CHP). Electricity is usually distributed to office applications and cooling devices. Thermal energy is used for space heating and other processes, such as equipment sterilization, laundry, and kitchen, etc. The most important factor that affects the feasibility of such investments is occupation and activity frequency as expressed by the capacity factor. Buildings like hospitals, hotels, schools can be the perfect candidate of such technologies since they have demanding thermal and cooling loads due to HVAC (heating, ventilating and air conditioning) systems. The evolution of the installed capacity of CHP technologies, along with the CHP share of different commercial consumers for 2014, is shown in Fig. 2. The dominance of gas driven technologies in this sector is prevalent. From the sigmoid curve it can be noticed that the market has passed the phase of the exponential growth and that it has reached its maturity.

However, there is still potential to be realized if certain barriers are lifted. In general, the barriers of distributed generation technologies fall into one of the following categories [5]:

- High initial costs
- Market risks for new technologies;
- Imperfect information;
- Uncertainty (technical, regulatory, policy, etc.).

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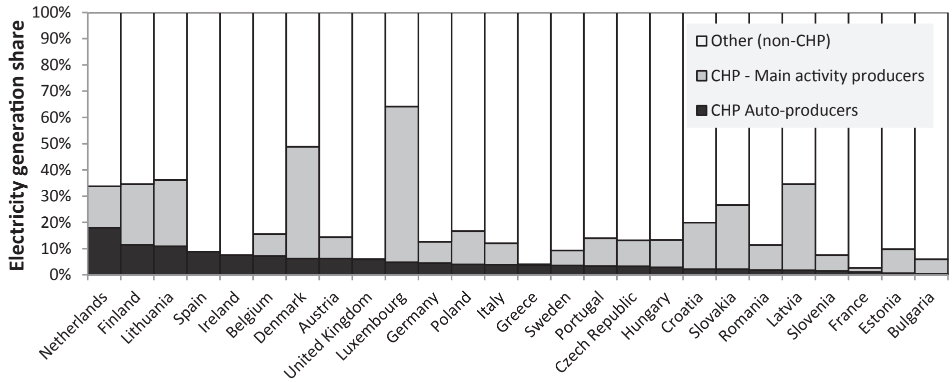

Fig. 1. Share of electricity generation of CHP autoproducers and main producers. Data source: [3].

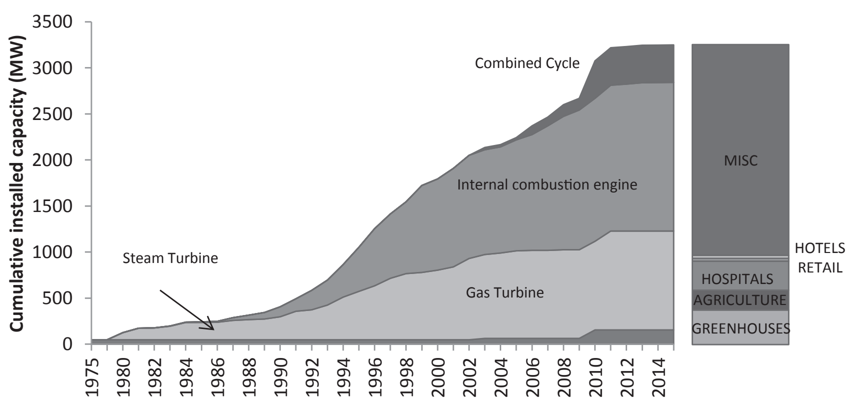

Fig. 2. Installed capacity in 2012 of CHP autoproducers per technology for tertiary sector. Data source: [4].

According to Baer et al. [6], the economic challenges of CHP investments are the greatest barriers to viability. Although CHP promises long-term energy-bill savings, companies often feel a greater financial risk because CHP installations have high upfront costs and long payback periods compared to traditional equipment. The recent economic crisis and the difficulties in securing financing have caused companies to become increasingly conservative, with even greater aversion to investments with longer payback periods.

EU Member States have recently reported the barriers of realization of the national potential of high efficiency cogeneration. The most important barrier – with 17 Member States reporting it – was the fuel prices and their volatility [7]. Other barriers in order of significance are: heating demand, law complexity, no support schemes, limited financial resources, regulatory framework uncertainties etc. A more recent study by Colmenar-Santos et al. [8] highlights this fact: price volatility and the regulatory framework are the most important barriers and without proper risk mitigation, these projects cannot be easily materialized. Investment opportunities of CHP scheme are difficult to evaluate due to the high complexity and multiple sources of risk [9]. CHP operators in EU have a particular uncertainty because low wholesale electricity prices have coincided with relatively high gas prices which is causing many plants to operate partially or not at all [10,11].

In order to better understand the barriers, it is necessary to examine the investment initiative of auto producers and how it differs to that of main producers. The investment dilemma of autoproducers consists of the decision whether cogeneration is more economical than conventional outsourced separate generation production means. The driving force of CHP investments is the energy savings, and the profits related to those savings are linked mainly to the prices of the competing fuels which are usually gas and electricity. It is evident that the more efficient the substituted equipment, the less attractive an energy efficiency investment is going to be. Another driver for distributed generation is the displacement of high-priced grid power with lower cost electricity generated onsite. Project economics are based on many project specific factors — size of system, total installed cost of the project, and local construction and labor rates. Production of energy is not the core business of the autoproducers, so a stable and risk-free environment is needed. In other words, these consumers (especially from the commercial and residential sectors) give advantage to systems that are simpler and not as price inelastic as cogeneration systems [12]. Hence, the viability of such installations is dependent on the substitution of the current equipment, market conditions, and the stability that is provided by the regulatory framework.

According to the above, it makes sense to study the theoretical relation between the viability of combined generation technologies and the market conditions and conventional equipment efficiency. In literature, there are some attempts for the use of such indicator. 'Spark spread', which refers to either the difference or the ratio of the competitive fuels i.e. natural gas and electricity, is the most common one. In an 'energy market' context it is usually the difference between electricity prices and gas prices multiplied by the heat rate which reflects the gross operation margin of a power plant [9,13]. Based on this difference, many financial products, such as options, have been used to hedge [14] and to estimate the value of such investments [13,15].

Dispatch decisions between competing technologies (e.g. cogeneration vs heat pumps) have also been based on this difference [16]. For CHP to be profitable, US Department of Energy Midwest CHP Application Center [17] proposes at least a difference of 0.04 $/kWh between natural gas and electricity. This rule of thumb refers only to CHP prime movers and does not consider the characteristics of substituted conventional equipment. However, other reports are using the price ratio to identify the feasibility of CHP. A latest report on European cogeneration [10] states that the ratio between electricity and fuel prices should be around 3 without any further justification and link to specific equipment. Cardona et al. [18,19] used this price ratio to develop an operation strategy which on an hourly basis can decide whether a CHP prime mover should operate or not. Graves et al. [20] developed a method that correlates the prime mover efficiency, the heat recovery ratio and the equipment cost as an indication of CHP viability. Smith et al. [21,22] have developed a similar indicator that is based on the operational characteristics of CHP but did not generalize it for the case of cooling production.

Literature review does not conclude to a generic feasibility indicator that correlates the energy prices with specific cogeneration technologies independent of the energy loads. Such indicators are being used extensively, but as discussed in the previous paragraph, the choice of values is governed by empiricism having limited applicability. Hence, the scope of this work is the development of a theoretical relation between energy prices and the characteristics of cogeneration and conventional generation equipment. Through this indicator, there will be an attempt to map the operational viability of co- and trigeneration equipment and to give a clear view of the sensitivity of energy prices on energy efficiency investments. This indicator will also be used to explore the feasibility of combined generation investments in EU and highlight the importance of energy pricing policy in order to minimize the risk exposure of energy efficiency investments.

2. Mathematical formulation of the proposed indicator

Fig. 3 shows the reference energy system that will be used for this study. An energy consumer demands three energy products (electricity, heating and cooling) at any given time. These loads can be covered by the following ways: either via combined generation (left side of Fig. 3) or via conventional generation technologies (right side of Fig. 3). The combined generation system consists of a prime mover (internal combustion engine, gas turbine etc) with heat recovery system and a thermal driven heat pump, such as an absorption chiller, which utilizes low grade heat. The conventional generation part consists of grid electricity, fossil fueled boiler and electric driven heat pump.

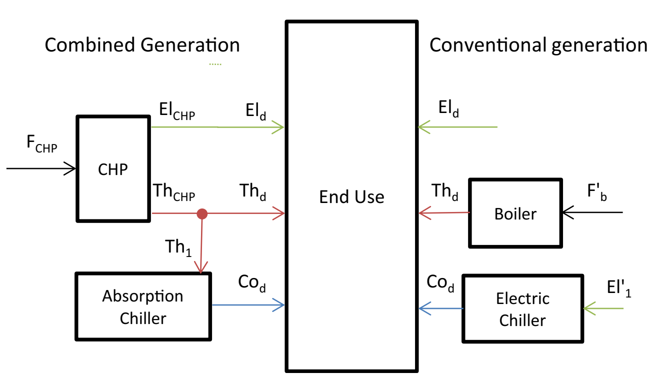

Fig. 3. Reference energy system for the coverage of specific energy demand by cogeneration and conventional generation.

In the context of this comparison, the energy that is covered by other sources is ignored (e.g. grid, boiler, electric chiller) and the energy that can be produced by a CHP system (with predefined technical characteristics) is compared for a given timeframe.

This system can be mathematically formulated as follows: Let El_d (kW), Th_d (kW) and Co_d (kW) be the energy demand for electricity, heating and cooling of an individual consumer respectively.

For the CHP part:

$$Th_{CHP} = Th_d + Th_1 \tag{1}$$

$$Co_d = COP_{ab} \cdot Th_1 \tag{2}$$

where COP_{ab} is the coefficient of performance of the absorption chiller.

From these equations and the definition of the overall CHP efficiency, it is derived:

$$\eta_{CHP} = \frac{\mathrm{El_{CHP}}}{\mathrm{F_{CHP}}} + \frac{\mathrm{Th_{CHP}}}{\mathrm{F_{CHP}}} \tag{3}$$

Similarly for conventional generation:

$$Co_d = COP_{El} \cdot El'_1 \tag{4}$$

$$Th_d = \eta_b \cdot F'_b \tag{5}$$

The hourly operational cost of trigeneration is defined by means of:

$$C_{CHP} = C_f \cdot F_{CHP} \tag{6}$$

whereas for the conventional (separate) generation by means of:

$$C_{SHP} = \mathrm{C_f} \cdot \mathrm{F}'_b + \mathrm{C_e} \cdot (\mathrm{El_d} + \mathrm{El}'_1) \tag{7}$$

where C_f (EUR/kWh), is the fuel price and C_e (EUR/kWh) is the electricity price. A necessary assumption to be made is that the electricity and fuel costs for both conventional and CHP generation of energy is the same. This may not be the case if special policies and subsidies are applied but it is useful to compare the inherent advantages and the true competitiveness of the two technologies.

As it was mentioned in the Introduction the basic investment motivation can be summarized as follows: When heating and electricity can be locally produced in smaller cost than the grid electricity and separate heat generation, then and only then a distributed generation CHP investment can operate with a profit.

For an economically viable operation of a trigeneration installation the operating costs of the CHP unit has to be less or equal than the conventional generation part for given energy loads:

$$C_{SHP} - C_{CHP} \geq 0 \tag{8}$$

where C_{CHP} and C_{SHP} (EUR) the operating costs of combined generation and conventional generation respectively as defined in (6) and (7).

Using the expressions (6), (7) and replacing F_{CHP} from (3), F'_b from (5), El'_1 from (4), and Co_d from (2), Eq. (8) becomes:

$$C_f \cdot \frac{Th_{CHP} - Th_1}{\eta_b} + C_e \cdot \left(El_{CHP} + \frac{Th_1 \cdot COP_{ab}}{COP_{el}} \right) - C_f \cdot \frac{El_{CHP} + Th_{CHP}}{\eta_{CHP}} \geq 0 \tag{9}$$

We define the ratio of electricity to natural gas price, $PriceRatio = C_e/C_f$ the heat to power ratio of the prime mover

$HPR = Th_{CHP}/El_{CHP}$ and the fraction of recovered heat that is used for cooling $a = Th_1/Th_{CHP}$. Replacing the above figures in Eq. (9) dividing by Th_{CHP}, simplifying and solving for *PriceRatio* the following equation is derived:

$$PriceRatio \geq \frac{COP_{el}[\eta_b + HPR(\eta_b - \eta_{CHP} + a\ \eta_{CHP})]}{\eta_b\ \eta_{CHP}(COP_{el} + COP_{ab}\ HPR\ a)} \tag{10}$$

For $\alpha = 1$, that is when all heat is used for the production of cooling in the absorption chiller the equation is simplified as follows:

$$PriceRatio \geq \frac{COP_{el}(1 + HPR)}{\eta_{CHP}(COP_{el} + COP_{ab}\ HPR)} \tag{11}$$

whereas for $\alpha = 0$, that is for simple cogeneration mode without an absorption chiller, the equation is simplified as follows:

$$PriceRatio \geq \frac{HPR + 1}{\eta_{CHP}} - \frac{HPR}{\eta_b} \tag{12}$$

The above relation covers only the operation feasibility ignoring the investment costs. Eq. (8) can be modified so that it calculates operational costs on an annual basis including an annualized capital costs term:

$$(C_{SHP} - C_{CHP}) \cdot CapF \cdot 8760 - crf(l,i) \cdot \left(C_{eq\ \ CHP} \cdot El_d + C_{eq\ \ ab} \cdot Co_d\right) \geq 0 \tag{13}$$

where $C_{eq\ CHP}$ the capital costs of CHP unit (EUR/kW$_e$) and $C_{eq\ ab}$ (EUR/kW$_c$) the capital costs of absorption chiller, crf (−) the capital recovery factor used to convert a present value into a stream of equal annual payments over a specified time (l), at a specified discount rate (i) by means of $crf = i(1+i)^n/(1+i)^n - 1$ and $CapF$ (%) the annual capacity factor of the cogeneration unit which is multiplied by 8760 (hours/year) to express the annual operating hours of the combined generation installation. This conversion is necessary for the dimensional consistence of the formula in order to express and compare all costs on an annual basis.

Eq. (13) is solved in a similar way but it cannot be simplified to a single price ratio due to an intercept term derived by the capital cost term. It will be shown in the results of the next section that the relation between the minimum gas price for a viable combined generation investment, varies linearly as a function of electricity prices ($C_f < a \cdot C_e + b$).

3. Results and discussion

3.1. Analysis of the developed indicator

Through the developed indicator the viability of different cogeneration technologies and configurations can be explored. The inequality (10) is not a function of the energy loads, but only a function of the technical specifications of the combined generation and conventional equipment. As it was mathematically proven, the operational viability is a function of the ratio and not the difference of the prices, as it is mentioned sometimes in literature. Converting this inequality expression to equality, the operational breakeven point is estimated, i.e. the price ratio for which CHP has same operating costs as conventional generation. The most important innovation of the described generalized formulation is that the minimum price spread can now be mathematically justified based on given technical specifications and not based on empiricism. The description of the inherent relationship of combined generation viability could allow the system operators to regulate their CHP system and the decision makers to quantify a minimum fuel subsidy in order to annihilate the operating risk of cogeneration units.

3.1.1. Operational viability

In the following paragraphs, the effect of the equipment's technical specifications to the minimum *PriceRatio*, for which a combined generation system can operate profitably, is shown. Table 1 shows typical parameters of an internal combustion engine based cogeneration unit. This type of unit is usually the ideal technology for middle scale cogeneration systems used in buildings of the tertiary sector. Typical values of the conventional heating and cooling generation systems are also considered.

The variable α can be used to simulate the seasonality effect of a combined generation device. During the summer months where a big percentage of heat is going to the absorption chiller, a tends to 1. On the other hand, during the winter α is usually 0 as all the recovered heat is used for other end uses (space heating, hot water etc.).

Fig. 4 shows that the bigger the amount of heat that is used for cooling the larger the *PriceRatio* has to be, i.e. the natural gas price has to be much smaller than the electricity price. This correlation is explained due to the non-efficient conversion of heat in the one-stage absorption chiller ($COP < 1$). This means that during summer months where the needs for cooling are bigger, the need for cheaper natural gas is bigger. If this is not the case then α has to be reduced by covering the cooling demand via separate production means. This observation comes in line with what is applied in practice; the operation and installation of an absorption chiller is not viable beyond a specific natural gas price threshold.

The technical characteristics of the combined generation equipment affect positively the minimum price ratio, whereas the characteristics of the substituted equipment negatively. The more efficient the new equipment and the less efficient the substituted equipment, the smaller is the requirement for a high electricity – gas price ratio (Fig. 5). Prime movers that produce more heat than electricity (for a given overall efficiency) are more sensitive in the variations of energy prices. For heating and electricity generation mode (no cooling) the heat power ratio has a very small effect. Regarding cooling equipment, as expected, Fig. 6 illustrates that the

Table 1
Typical values for parameters of Eq. (10).

Parameters of equation	Variable	Central value
Coefficient of performance of electric chiller	COP_{el}	3.5
Coefficient of performance of absorption chiller	COP_{ab}	0.8
Boiler Efficiency	η_b	85%
CHP overall efficiency	η_{CHP}	90%
Heat to power ratio of prime mover	HPR	1.2

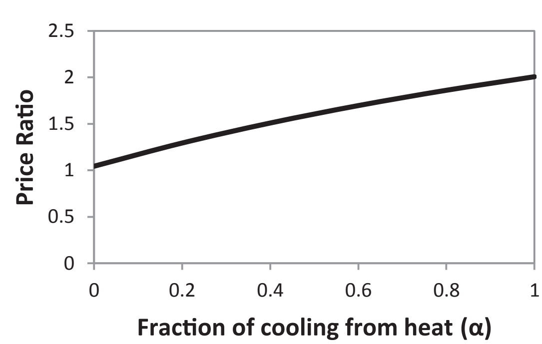

Fig. 4. Effect of cooling fraction from recovered heat on the minimum *PriceRatio*.

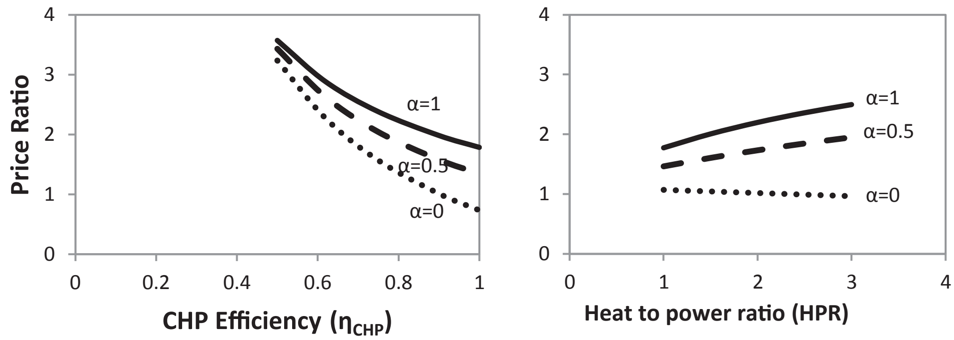

Fig. 5. Effect of CHP prime mover characteristics on the minimum *PriceRatio*.

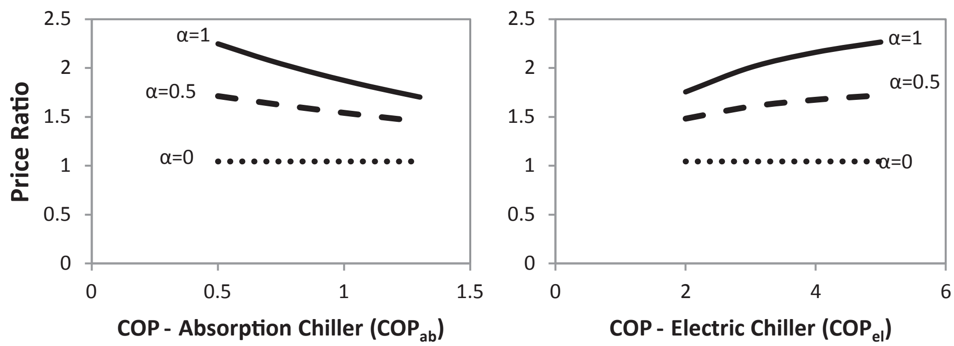

Fig. 6. Effect of COP on the minimum *PriceRatio*.

conventional and the cogeneration equipment have an inverse relationship; the bigger the COP (coefficient of performance) of the electric chiller and the lower the COP of the absorption chiller, the higher the minimum *PriceRatio* has to be.

The efficiency of the conventional boiler is apparently the most important variable (Fig. 7), especially for operating conditions with small α (no cooling). If the equipment substitutes old non efficient equipment then the profit margin is very large. *PriceRatio* can even fall below one i.e. CHP will be viable even if electricity prices are smaller than natural gas prices. In old and inefficient boilers, the CHP unit will be able to operate in any gas price, depending on cooling fraction from heat as defined by α.

3.1.2. Investment viability

The above analysis was done for existing cogeneration devices. For new investments the capital cost and the operating time of the equipment has to be accounted by means of Eq. (13). In order to make clear the interactions between the critical variables and economic feasibility of new investments described in the previous sections, a simple sensitivity analysis is conducted. The plotted line in Fig. 8 corresponds to the locus of the points where total annual costs (including depreciation of investment) of separate production are the same as in the cogeneration case (investment break even line). In order to illustrate better the difference between heating ($a = 0$) and cooling mode ($a = 1$), two breakeven charts were plotted. For the combination of prices that fall within the area above each line, separate production is more economical. In the area below the line, cogeneration is more economical. Three different prime movers are compared: ICE (internal combustion

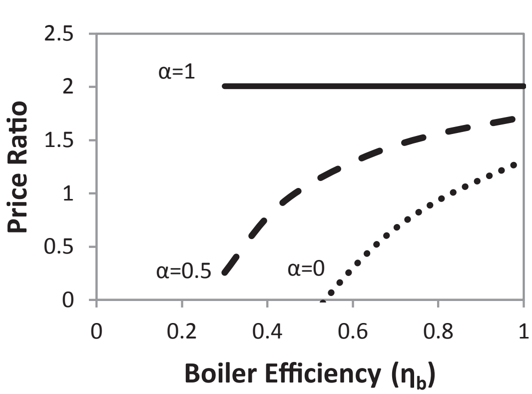

Fig. 7. Effect of substituted boiler efficiency on the minimum *PriceRatio*.

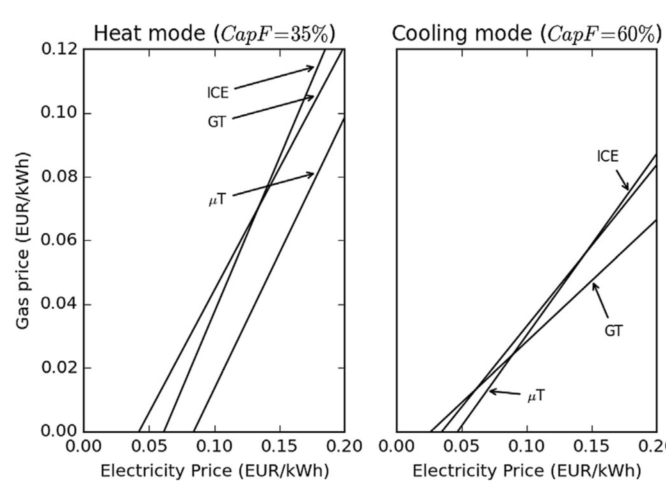

Fig. 8. Investment break-even point for different prime movers and operation modes.

Table 2
Cost assumptions for technology comparison.

Parameters of equation	Variable	ICE	GT	μT
Capital cost of prime mover	$C_{eq\ CHP}$ (EUR/kWe)	1600	1100	2200
Capital cost of absorption chiller	$C_{eq\ ab}$ (EUR/kWc)	400	400	400
Overall efficiency	η_{CHP}	90%	82%	85%
Heat to power Ratio	*HPR*	1.2	2	0.7
Capacity factor	*CapF* (%)	Depends on load (assumed 35% for heat only and 60% for heat and cooling)		
Discount rate	*i* (%)	10%		
Investment lifetime	*n* (yrs)	20		

engine), GT (gas turbine) and μT (microturbine). The technology parameters assumed are presented on Table 2. Parameters from conventional equipment are adopted from Table 1. It has to be noted that a higher capacity factor applies to heating and cooling mode (trigeneration) due to the fact that the co-produced thermal load will be able to be utilized during all the periods of the year increasing the operation period.

According to Fig. 8 for a typical ICE system and assuming that nowadays gas prices fall within the region of 0.05–0.08 EUR/kWh, combined generation investments will be feasible if electricity prices are over 0.11–0.14 EUR/kWh assuming full heating mode, or over 0.13–0.18 EUR/kWh with cooling mode. For low electricity prices (<0.06 EUR/kWh) cooling mode can be profitable even when heating mode is not, due to the fact that a higher capacity factor, i.e. a higher coverage of the loads by the cogeneration equipment is assumed. In other words, the added value of combined heating and cooling is not based on the inherent increased efficiency – after all conventional low temperature heat-driven absorption chillers have very low efficiency – but to the value that the dispatch flexibility adds to the system.

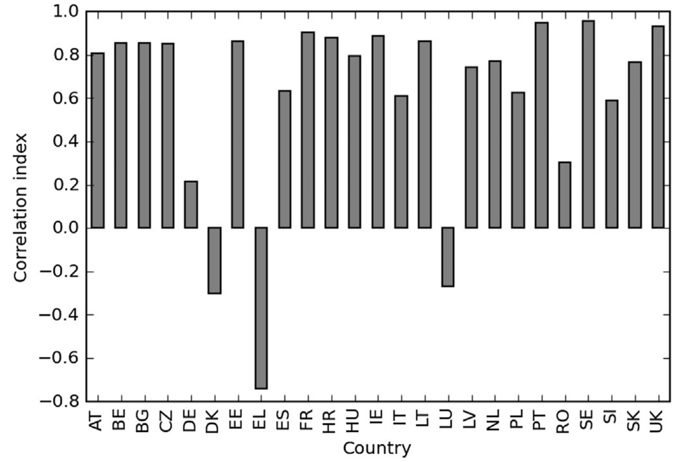

Fig. 11. Correlation of historical data (2007–2014) for EU-28 electricity and gas prices.

3.2. Current situation and prospects for combined generation in EU-28 countries

The indicator developed can be used to explore the European market, of co- and trigeneration units. The evolution of electricity and gas prices (where applicable) of tertiary sector consumers of EU-28 is presented in Fig. 9 and the derived price ratios in Fig. 10. As a reference the operational feasibility limits are shown for full heat mode or full cooling mode as estimated in Fig. 4. Currently it seems that there are a few countries that are close to the operational feasibility point. Indeed these countries e.g. Bulgaria, France and Sweden, have low market share of CHP autoproducers (see Fig. 1) due to low price ratios. In most cases the fluctuation of electricity

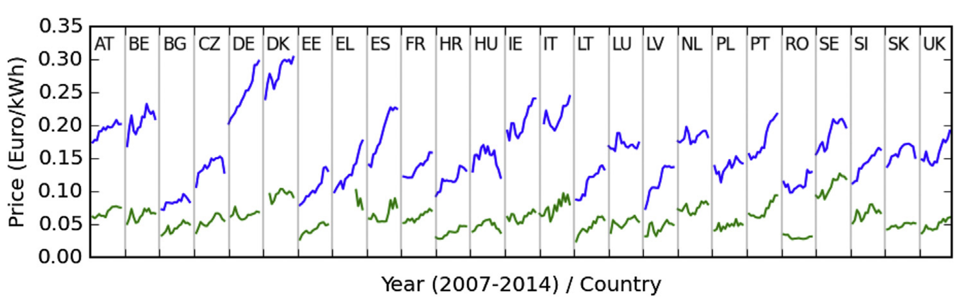

Fig. 9. Timeseries of natural gas prices (green) and electricity prices (blue). Adapted from the high consumption band of non-industrial pricelist: heat >200 GJ and electricity above >15 000 kWh. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

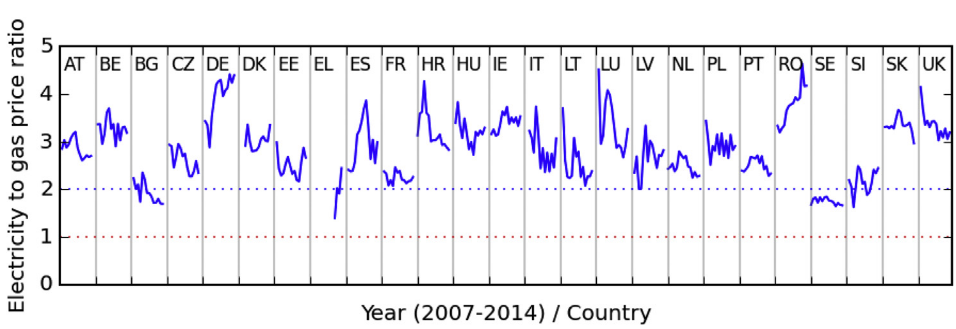

Fig. 10. Historical data of *PriceRatio* for EU-28 countries. The red and blue dotted line show the operational viability limit of a typical ICE based CHP unit based on results of Eq. (10) for full heating or cooling mode respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

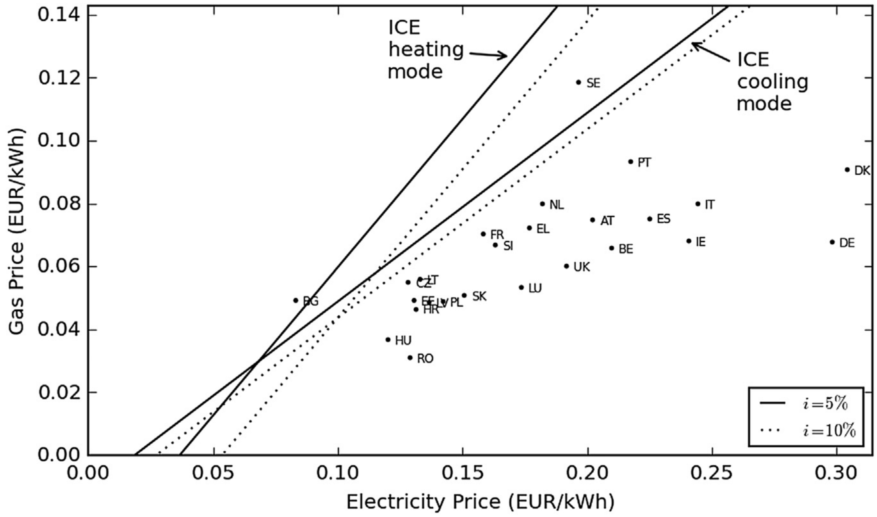

Fig. 12. Gas and electricity prices of EU-28 countries for 2014. The black lines represent the investment break even points based on Eq. (13) with or without production of cooling for 2 discount rates (5% and 10%).

and gas prices has a positive correlation (Fig. 11). In some cases there is weaker correlation due to either an inaccurate pricing mechanism of natural gas or a smaller dependence of electricity production from fossil fuels.

Similarly the investment driving force for CHP autoproduction is shown in Fig. 12 for all countries. For the sake of clarity only one prime mover technology is shown for two discount rates and two operation modes. The further each point from the line, the less attractive an investment is. Countries like Denmark and Germany have the strongest driving force for the investments on autoproducer CHP technologies. A group of countries which is close to the break even line may not have a strong driving force that can justify the risk exposure for future investments without effective policies. Bulgaria is the only country above the breakeven line i.e. infeasible investment, which explains the fact that it is the last country in the market share of autoproducers (Fig. 1).

4. Conclusion

According to current data, combined generation technologies for autoproducers have already been deployed but further policy support is needed to overcome the current barriers. The indicator developed was an attempt to untangle the complex relationship between economic profitability, equipment, and energy price ratio. It can be used to overview the profitability potential of distributed combined generation investments in any free or regulated market. A price ratio was interpreted as a measure of the system's variable operating margin. High volatility in energy prices caused by policies, technology improvements and geopolitical developments, make CHP profitability fluctuate. For capital investments of CHP the capacity factor is also a critical parameter. Depending on the load coincidence characteristics, it is possible to increase the capacity factor by introducing a heat driven chiller since the co-produced thermal load will be able to be utilized during all the periods of the year. However, due to its lower coefficient of performance of the absorption chiller, it needs a more attractive Price Ratio. This trade-off between capital costs of a chiller and higher capacity factors has to be examined on a case per case basis and depends highly on the load profile characteristics. In other words, the competitive advantage of trigeneration compared to simple cogeneration is not attributed to the native technological efficiency improvement but to the higher flexibility and wider field of application.

Policy support to combined generation investments can be provided by reducing the natural gas price that is feeding CHP either by subsidizing it or by fixing a minimum price ratio as a tax-based mechanism to hedge the risk of fuel price fluctuations. The developed indicator can be used as a tool to quantify the risk to the exposure of such investments. Alternatively a feed in tariff can be applied to the produced electricity provided that the unit covers the heating and cooling loads. However such subsidies would go to existing CHP plants rather than new plants. Other forms of subsidy like capital incentives or tax reduction measures may be effective for the deployment of such units but without avoiding the operational risk of the volatile prices. Such measures, promoting combined generation systems that utilize the primary energy of fuel more efficiently, when designed correctly can have a huge impact on achieving both energy savings and emission reduction targets.

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Nomenclature

C	Operating Costs, EUR
CC	Capital Costs, EUR
CHP	Combined Heating and Cooling
Co	Cooling energy, kW
COP	Coefficient of Performance, –
El	Electricity, kW
F	Fuel, kW
GT	Gas Turbine
HPR	Heat Power Ratio, –
ICE	Internal Combustion Engine
PESR	Primary Energy Savings Ratio, %
Th	Thermal energy, kW
α	Fraction of cooling from heat, –
η	Efficiency, %
μT	Microturbine

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